Embedded Optical Sensors for Thermal Barrier Coatings

Final Technical Report

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Abstract

The concept of non-contact luminescence sensing of temperature in thermal barrier coatings has been elaborated and reduced to practical realization during the course of the work supported by this NETL contract. The concept we have introduced, investigated and demonstrated is using the characteristic features of the luminescence from rare-earth dopant ions incorporated into the crystal structure of thermal barrier coatings to provide a direct measurement of temperature. By placing the dopant ions, by either electron-beam evaporation or plasma-spraying, into specific locations in the coating during fabrication the temperatures at those locations can be monitored. The luminescence is excited with a laser probe so local, non-contact temperature measurements can, in principal, be made by focusing the laser probe to parts of a blade or other coated component that are of interest. The detailed description of the program activities and accomplishments are described in the earlier annual reports and publications so only a summary will be presented in this final report.

During the course of the contract, several candidate rare-earth ions as luminescence doping of both the commercial thermal barrier coating materials, yttria-stabilized zirconia and gadolinium zirconates, have been investigated. Although several rare-earth ions, including Dy^{3+}, Sm^{3+} and Er^{3+}, were found to have attractive temperature capabilities, europium (Eu^{3+}) was found to be the optimum. Measurement of temperatures in excess of 1150^{o}C of thermal barrier coatings have been demonstrated under both furnace conditions and thermal gradient tests. The sensing capabilities have been shown to be stable even after exposures of 200 hours at 1450^{o}C, far in excess of the life of current thermal barrier coatings. Compact, fiber-optic based instrumentation has also been developed for utilizing the luminescence sensors and is suitable for remote application as well as for use in actual turbine monitoring.

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1. Executive Summary

During the course of the work supported by the NETL contract the concept of non-contact luminescence sensing of temperature in thermal barrier coatings has been elaborated and reduced to practical realization. The concept we have introduced, investigated and demonstrated is incorporating thin layers of dopants into the crystal structure of thermal barrier coatings and using the characteristic features of the luminescence from the dopant ions to provide a direct measurement of the temperature in the coating where the dopants are positioned during fabrication. The luminescence is excited with a laser probe so local temperature measurements can, in principal, be made by focusing the laser probe to parts of a blade or other coated component that are of interest. The detailed description of the program activities and accomplishments are described in the earlier annual reports and publications so only a summary will be presented in this final report.

The principal motivation for this work is that the life of thermal barrier coatings used in gas turbines is dependent on their temperature, particularly on the temperature of the bond-coat alloy immediately beneath the thermal barrier coating. This is because the majority of mechanisms responsible for coating failure are thermally activated processes and hence are exponentially dependent on temperature. Consequently, temperature measurement is of paramount importance if reliable life predictions are to be made.

2. Personnel.

The NETL grant supported, in part, the research studies of a PhD student, Ms Molly Gentleman. She is now a staff member at General Electric's Global Research Center, where she is working on various, company proprietary, energy-related projects including turbine materials.

3. Background.

3.1. Sensor Concept.

The basis of the embedded temperature sensor is the temperature dependence of the luminescence lifetime of selected rare-earth ions incorporated into the crystal structure of the thermal barrier coating. As the rare-earth ions are part of the crystal structure of the coating material, the sensing is embedded at the atomic level in the coating and, as distinct from conventional sensors, is not a separate sensor element. Two different coating materials were studied, yttria-stabilized zirconia (YSZ) and gadolinium zirconate (GZO). The former is the thermal barrier material of choice in the majority of engines whereas the latter is used in certain specialized applications by United Technologies (Pratt and Whitney). It is also of growing interest to companies overseas in Europe, Japan and China as well as Siemens.

4. Experimental

4.1. Instrumentation.

An integral part of the program activities has been the development of a sensing system that excites the luminescence, collects the luminescence at high temperature and analyzes it to provide a temperature measurement. Our system uses a small solid state laser to excite the luminescence and a sapphire or fused silica fiber optic to collect the luminescence. The high temperature fiber optic is spliced to standard optical fibers and the luminescence passed through a series of optical filters to a solid-state photomultiplier. Its electrical output is sent through a USB connector to a storage oscilloscope and computer. The laser pulse is triggered, the temporal evolution of the luminescence collected and the spectral accumulation are all under computer control. The use of the optical filters simplifies the instrumentation, as well as making it more compact, by avoiding the need to use a monochromator and associated moving parts. The system was designed to not only provide a compact and easily transportable system but also with a view to its use on an actual gas turbine engine.

5. Results and Discussion

5.1. Sensor Material Development.

One of the major tasks we addressed was the selection of appropriate rare-earth dopants for luminescence sensing of thermal barrier coatings and the determination of the optimum dopants and concentrations. Systematic studies of the temperature dependence of the luminescence from various rare-earths in both yttria-stabilized zirconia (YSZ) and gadolinium zirconate (GZO) revealed that although several rare-earth dopants could be employed, europium was in many respects the optimum. Specifically, it exhibited measurable temperature sensitivity up to 1150^{o}C , its strongest emission occurs at 606 nm, a wavelength at which any black-body radiation is minimal compared to longer wavelength rare-earth sensors, and it can be excited efficiently by a range of common laser excitation wavelengths. The luminescence lifetime-temperature characteristics were also insensitive to dopant concentration over a wide range of compositions.

5.2. Sensor Coatings.

A number of different luminescence sensor configurations were fabricated and tested. The majority were fabricated by electron beam deposition although a number of test samples were also fabricated by plasma-sprayed deposition, the other industrial method of producing thermal barrier coatings. Typical sensor coatings consisted of a 10 micron-thick Eu-doped YSZ layer either deposited directly on a superalloy substrate and covered by a standard, undoped YSZ coating, or the 10 micron-thick Eu-doped YSZ layer deposited on top of a standard YSZ coating. These were used to measure temperatures at the alloy/TBC interface and at the TBC surface, respectively.

5.3. Long term stability tests.

One concern in any sensor system, especially an embedded one, is whether the sensor affects the life of the component it is embedded in and whether its' sensing capabilities are stable over the life of the component. To address these concerns, standard EB-PVD coatings containing embedded Eu-doped layer sensors were subject to two types of tests: one-hour thermally cycle tests between room temperature and 1150^{o}C, and long-term isothermal tests at 1450^{o}C. (The long-term tests included a low-temperature aging step to accelerate the transformation of the YSZ coatings to the monoclinic phase, a transformation considered in the turbine materials community to be detrimental to coating life). The thermal cycled sensor coatings exhibited the same average cycle life as coatings without the sensor layers, and with no change in the temperature sensing characteristics. The long-term isothermal tests together with accelerated aging revealed no change or degradation in the luminescence sensing capabilities of the sensor. Together, these observations provide confidence that the temperature sensing capabilities of the sensor are stable for extended times at high-temperatures appropriate to engine applications and without causing premature failure. Further testing to provide meaningful statistical lifetime data in the form of Weibull distributions is required but the results obtained in this program suggest that there are no physical reasons to indicate that the luminescence degrades with long-term exposure at high temperatures or that the presence of the sensor compromises the life of coatings produced by current production deposition methods.

6. Conclusions.

Potential for application in gas turbine operation: An assessment.

The work performed under the current contract demonstrates the feasibility of the luminescence concept for measuring temperature. A preferred luminescent dopant (europium) has been identified, the temperature-dependence of its luminescence lifetime has been measured up to 1150^{o}C in air, thermal barrier coatings containing thin layers of the dopant have been fabricated by processes currently employed by industry in manufacturing thermal barrier coatings, temperatures have been measured *in-situ* in thermal gradient tests at NASA Glenn and the presence of the luminescence dopant has not compromised the life of the coatings tested. Furthermore, a compact fiber-optic based sensor system has been developed. An important feature of the luminescence technique that lends itself to measurements on rotating components is that the lifetimes at high temperatures are extremely short, tens to hundreds of nanoseconds at temperatures in the range of 950-1150^{o}C. Consequently, measurements can, in principal, be made much faster than the speed at which a blade passes by a fixed laser beam. Calculations also indicate that scanning over hot portions of individual blades should be feasible with synchronization with the turbine rotation.

These advances indicate that the major phase of materials development for the sensors is completed and the next level of technological development is to demonstrate that the sensor can be implemented in an engine configuration for temperature measurement of both stationary and rotating components. This requires access to a demonstration engine and the availability of an optical access port. The latter is apparently available on some power generation engines but the principal difficulty is to obtain permission for access from one or more of the engine manufacturers.

References ------ None included

Bibliography ---- None included

Appendices ------ None included